Persistent Current Effects in HERA-p

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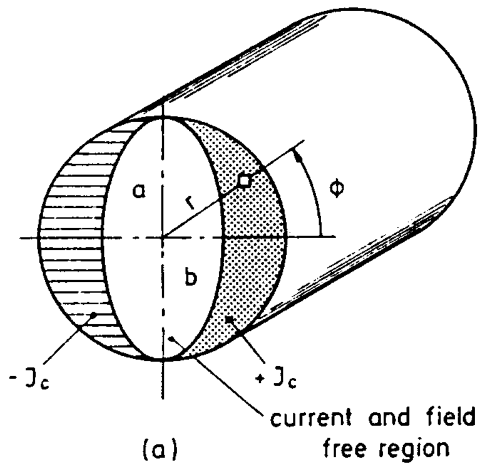

Figure 1: Schematic view of persistent currents inside a filament, running back and forth at a critical current J_c [1]

Abstract

Eddy currents in the filaments of superconducting magnets, so called persistent currents, are of great concern for any accelerator using superconducting magnets, like HERA, RHIC, TEVATRON, or LHC. Persistent current effects on the chromaticities in the HERA proton machine during injection are presented, with an emphasis on their predictibility and reproducibility.

1 INTRODUCTION

In recent years superconducting magnets have become the state-of-the-art technology for high energy hadron machines, like HERA, TEVATRON, RHIC, or LHC. As for all accelerators, the reproducibility and predictibility of magnetic fields and thus optics parameters is of great importance for the successful operation of the machine.
Persistent currents are eddy currents induced within the filaments of superconducting magnet windings by changes of the magnetic fields. These persistent currents circulate inside the filaments at a constant current density, as schematically shown in figure 1. Since they contribute to the multipole components of the magnetic field, persistent currents severely affect the quality of a superconducting magnet, especially at low magnetic fields. The azimuthal field component B_θ as a function of the radius r and the azimuth angle θ can be expanded in a series of normal and skew components as

$$B_\theta(r,\theta) = B_{\mathrm{main}} \cdot \sum_n \left(\frac{r}{r_0}\right)^{n-1} \cdot \cdot [b_n \cdot \cos(n\theta) + a_n \cdot \sin(n\theta)], \quad (1)$$

with

r_0	reference radius
b_n	normal multipole coefficient
a_n	skew multipole coefficient
B_{main}	main field
	(dipole field,
	or quadrupole gradient $\cdot\, r_0$).

In the case of HERA, the chosen reference radius $r_0 = 25\,\mathrm{mm}$ equals approximately the free-bore radius of the beam pipe.
The effect of persistent currents on the multipole components of the superconducting magnets can be completely neglected at high magnetic fields of about $5\,\mathrm{Tesla}$, which in the case of HERA corresponds to a proton energy of $920\,\mathrm{GeV}$. As measurements have shown, all higher-order multipole coefficients are of the order of 10^{-4} in that case. This changes drastically at the injection energy of $40\,\mathrm{GeV}$, corresponding to $0.2667\,\mathrm{Tesla}$. Here, multipoles of all orders allowed by the coil geometry are induced, i. e. $n = 1, 3, 5, \ldots$ within dipole magnets and $n = 2, 6, 10$ in the case of quadrupole magnets.
As a consequence, the chromaticities of the HERA proton ring at injection energy are completely dominated by persistent current sextupoles. While the natural chromaticities amount to $\xi_x = -44$ in the horizontal and $\xi_y = -47$ in the vertical direction, the contribution of the induced persistent current sextupoles due to the b_3 component in the dipole magnet of $b_3 \approx 3.2 \cdot 10^{-3}$ is about a factor of 5 higher [3]:

	natural	b_3 (dipoles)
ξ_x	-44	-275
ξ_y	-47	+245

To make things even worse, the influence of persistent currents on machine performance depends strongly on the history of the magnets – duration of the previous run, quenches, etc. Additionally, persistent current effects vary with time due to their decay [4]. For successful operation of the accelerator some means of compensation is therefore necessary.

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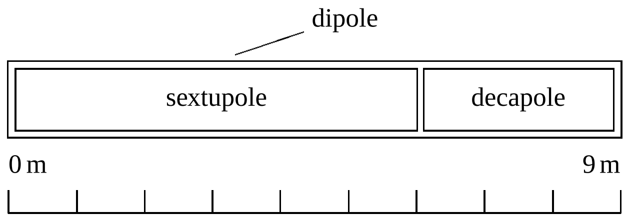

Figure 2: Schematic view of a superconducting HERA dipole with its sextupole and decapole correction windings.

2 THE HERA PERSISTENT CURRENT SEXTUPOLE CORRECTION SCHEME

The superconducting HERA dipoles are equipped with quadrupole and sextupole windings in order to correct field distortions. While the total length of the dipole is $9.0\,\mathrm{m}$, the length of the sextupole winding is only $5.9\,\mathrm{m}$. Furthermore, the sextupole coil is not longitudinally centered with respect to the dipole winding, but is shifted to one end, while the remaining space is equipped with a decapole coil. This is schematically shown in figure 2. To compensate the effects of decaying persistent currents at injection and of induced persistent currents during the ramp, two reference magnets are connected in series with the main HERA-p dipoles [5]. These reference magnets are equipped with various measurement devices, like NMR, hall probes, and rotating coils, in order to determine the actual multipole components of the magnetic field [6]. During injection, these measurements are used to compensate time-dependent contributions of decaying persistent currents to the dipole and sextupole fields, while during the first stage of the ramp, from injection energy to $150\,\mathrm{GeV}$, this system counteracts the "snap-back" effect of the newly induced persistent currents.

At the end of a luminosity run, the magnets are cycled in a well-defined procedure in order to achieve reproducible injection conditions of the magnetic fields on their hysteresis curve. During this procedure, persistent currents are induced which would lead to extremely unstable injection parameters.

When the injection energy is finally reached, these persistent currents decay exponentially. Since the absolute field variation is large immediately after cycling the magnets, the compensation of the effect of this decay on the chromaticity starts with a delay of $300\,\mathrm{sec}$ in order to keep the necessary sextupole correction fields small. The effect of the obtained persistent current sextupole contribution on the chromaticities is automatically kept constant using the two sextupole families installed in the HERA proton ring.

Figure 3 shows the chromaticities at injection during 30 minutes with and without this sextupole correction. When the sextupole correction is switched off, the decaying persistent currents lead to a rapid change of the chromaticities. With the sextupole correction switched on, the chromaticities stay constant within the measurement accuracy.

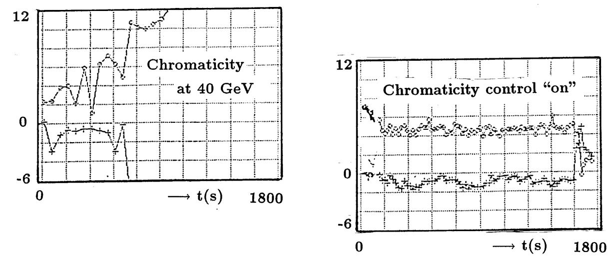

Figure 3: Chromaticities of the HERA proton ring during 30 minutes at injection energy. The left plot shows the rapidly changing chromaticities due to decaying persistent currents when the sextupole correction is switched off. With the sextupole correction switched on, the chromaticities remain constant (right plot) [2].

3 REPRODUCIBILITY AND PREDICTIBILITY OF PERSISTENT CURRENT SEXTUPOLES

While the HERA persistent current setupole correction scheme presented in the previous section compensates the effect of the persistent current decay, the absolute values of the chromaticity are adjusted using measurements on beam. For this purpose, a test beam of 10 proton bunches is injected which is used to measure and correct several parameters, such as energy (dipole field), tune, coupling, and chromaticities. When these parameters are adjusted, the test beam is dumped, and the luminosity fill of $3 \cdot 60 = 180$ bunches is injected.

Since the persistent current sextupole contribution is known from the reference magnet measurement, one might think of using it for the adjustment of the absolute chromaticities instead of the beam-based measurement. To test the feasibility of such a scheme the chromaticities are calculated using the measured b_3 component and the actual sextupole fields necessary to obtain chromaticities of about $\xi_{x,y} = +2 \pm 1$, as required for stable operation of the machine. If these calculated chromaticities are constant within one or two units, the reference magnet field measurements should be sufficient to adjust the chromaticities.

Figure 4 shows the optics of one of the 104 FODO cells in the arcs of the HERA proton ring. The persistent current sextupoles, which have the same length and location as the dipole coils, are represented by a thin sextupole of $10\,\mathrm{mm}$ length, located in the longitudinal center of the decapole winding (see figure 2). The correction sextupoles are assumed to be located in the longitudinal center of their actual winding, with a length of $10\,\mathrm{mm}$.

Within the four dipole magnets, both the square-root of the β-functions, $\sqrt{\beta_{x,y}}$, and the horizontal dispersion, D_x, vary approximately linearly with the longitudinal coordinate s along the orbit. Since the contribution of sextupoles

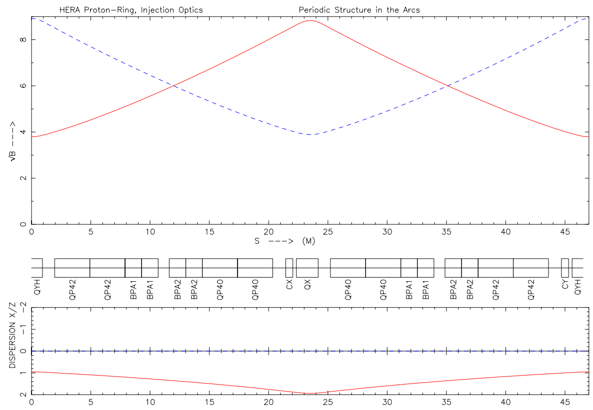

Figure 4: FODO cell optics used for the calculation of the chromaticities due to persistent current sextupoles and correction sextupole settings.

with strength $m(s)$ to the chromaticities depends linearly on the β-function and the horizontal dispersion,

$$\xi_{x,y,\mathrm{sext}} = \frac{1}{4\pi} \oint D_x(s)\beta_{x,y}(s)m(s)\,\mathrm{d}s, \tag{2}$$

the appropriate representation by thin lenses between dipole slices is a crucial issue.
Figure 5 shows the chromaticities as obtained from the b_3 measurement and the actual sextupole settings. In both planes the calculated chromaticities are found within a band of about ± 5. As usual, the chromaticities are aimed to be $\xi_x = \xi_y = +2 \pm 1$, and must not be negative in order to avoid the head-tail instability. Since the measured bandwidth of ± 5 would frequently lead to negative chromaticities, this shows that the b_3 measurement in the reference magnets is not sufficient to predict and correct the chromaticities of HERA-p. A possible explanation is the simplified optics model used in this calculation, which does not reflect the longitudinal positions of the persistent current sextupoles and the "real" machine sextupoles well enough. Additionally, the reference magnets might not reflect the average persistent current sextupoles in the entire machine to a sufficient accuracy.

4 SUMMARY AND OPEN QUESTIONS

As has been shown, the predictibility of persistent current effects on the chromaticities in the superconducting HERA proton ring at injection energy does not seem to be sufficiently accurate to ensure a successful operation of the machine without chromaticity measurements using a test beam. At present it is still unknown whether this irreproducibility is probably just due to the simplified optics model used in these investigations. In order to improve this situation, a refined optics model will be developed for further studies, with a more realistic representation of both persistent current and correction sextupoles by an increased number of slices.

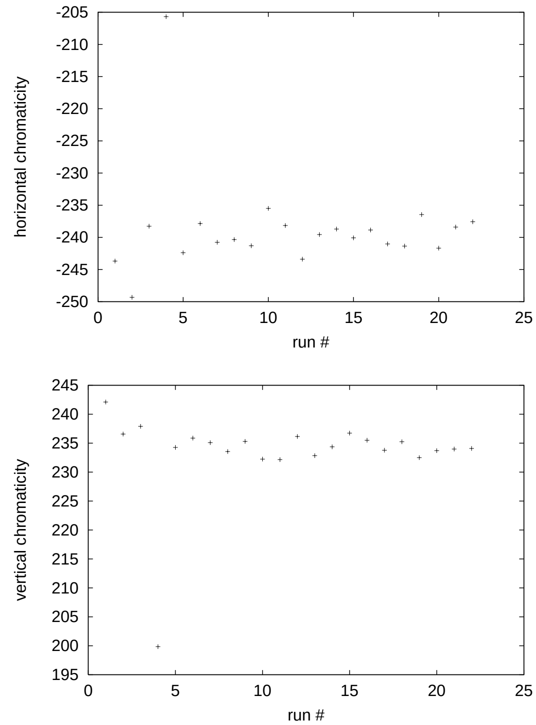

Figure 5: Calculated chromaticities versus run number. The large deviation from the mean value during run 4 is likely to be due to errors in data taking.

Furthermore it is planned to study the reproducibility and predictibility of persistent currents on the machine energy, i. e. the dipole field, the tunes, and the betatron coupling.

5 REFERENCES

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